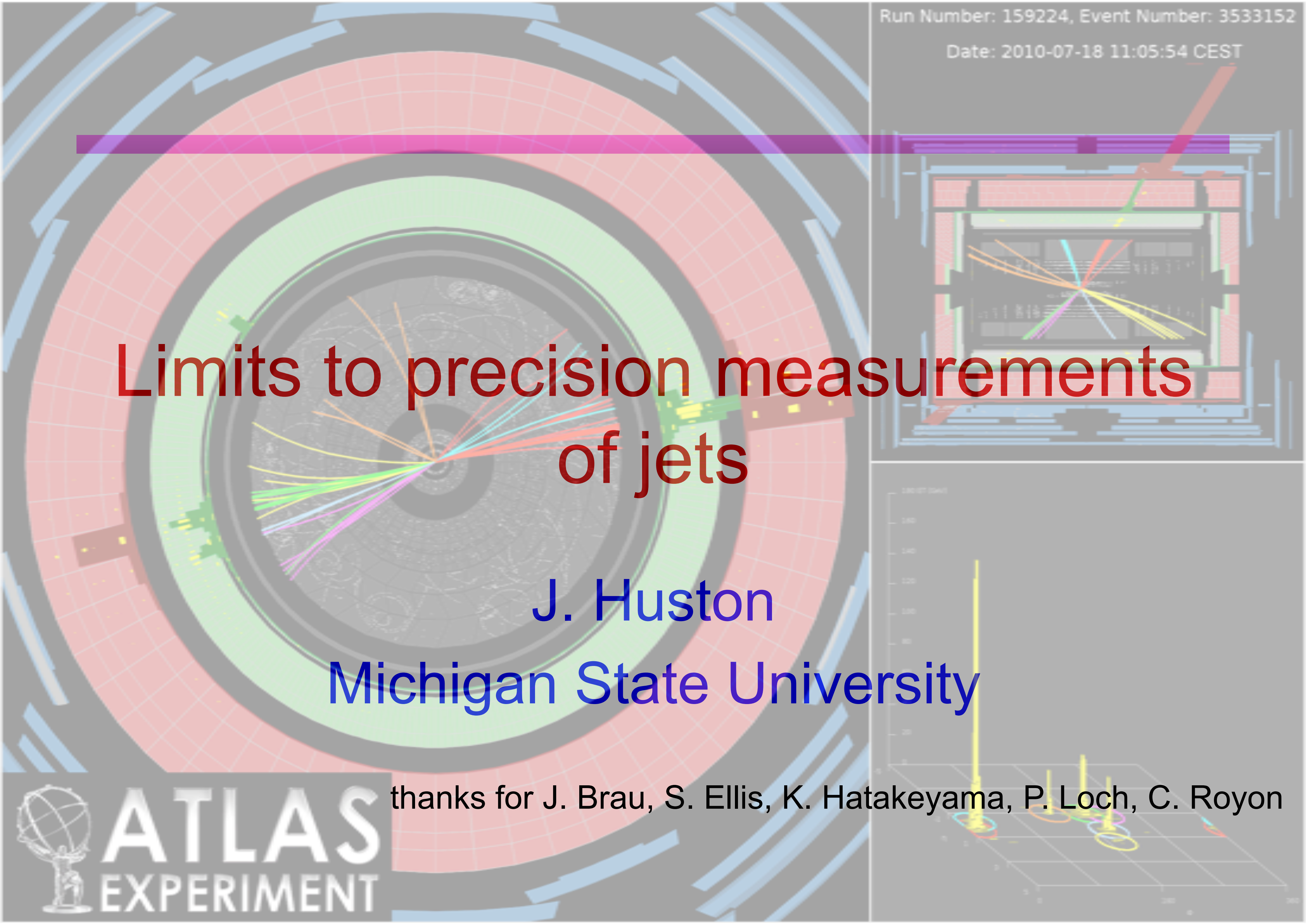
Limits to precision measurements of jets

J. Huston
Michigan State University

thanks for J. Brau, S. Ellis, K. Hatakeyama, P. Loch, C. Royon



Some references

Towards Jetography

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Abstract

As the LHC prepares to start taking data, this review is intended to provide a QCD theorist's understanding and views on jet finding at hadron colliders, including recent developments. My hope is that it will serve both as a primer for the newcomer to jets and as a quick reference for those with some experience of the subject. It is devoted to the questions of how one defines jets, how jets relate to partons, and to the emerging subject of how best to use jets at the LHC.

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Review

Jets in hadron–hadron collisions

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Abstract

In this article, we review some of the complexities of jet algorithms and of the resultant comparisons of data to theory. We review the extensive experience with jet measurements at the Tevatron, the extrapolation of this acquired wisdom to the LHC and the differences between the Tevatron and LHC environments. We also describe a framework (SpartyJet) for the convenient comparison of results using different jet algorithms.

Keywords: Jet; Jet algorithm; LHC; Tevatron; Perturbative QCD; SpartyJet

Contents

A briefer reference

explain it in 60 seconds

Jets are sprays of particles that fly out from certain high-energy collisions—for instance, from violent collisions of protons and antiprotons at Fermilab's Tevatron accelerator, or in the similar proton-proton collisions that will take place at CERN's Large Hadron Collider.

These collisions create very energetic quarks and gluons; as they travel away from the collision point, they emit more gluons, which can split into even more gluons. This results in a relatively narrow cascade, or jet, of particles.

In the last stage of jet creation, quarks and gluons combine to form particles such as protons, pions, and kaons. By measuring these end products, physicists can determine the properties of a jet, and thus the details of the collision that produced it. Scientists expect to see jets in the signatures of almost every interesting collision at the Large Hadron Collider.

The most violent collisions will produce jets with the highest momentum, and these can be used to probe the smallest distances within the colliding protons, less than one-billionth of a billionth of a meter. Physicists hope they can use these most energetic jets to look inside the quarks that make up protons.

Joey Huston, Michigan State University

"When you're a jet, you're a jet all the way, from your first gluon split to your last K decay..."

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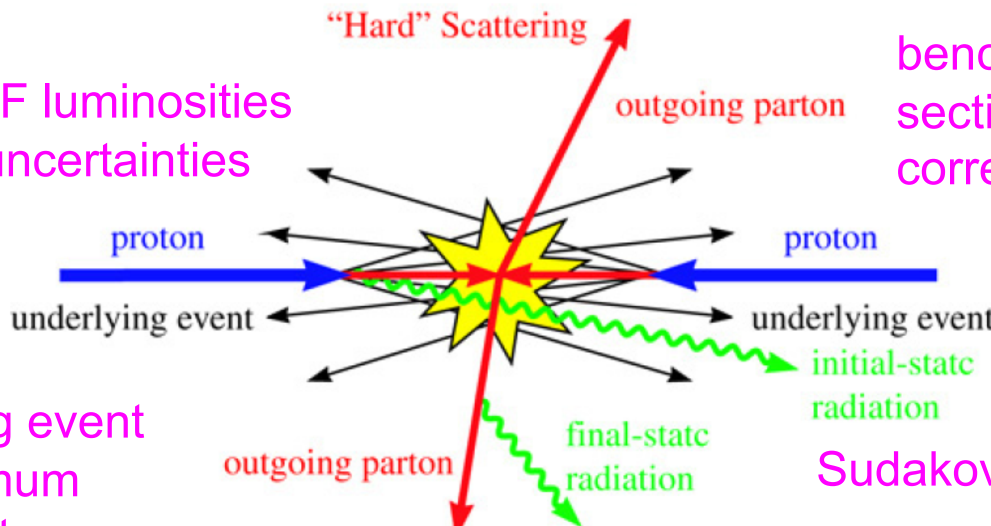
Understanding cross sections at the LHC

…means understanding QCD at the LHC

LO, NLO and NNLO calculations
K-factors

PDF’s, PDF luminosities
and PDF uncertainties

benchmark cross
sections and pdf
correlations



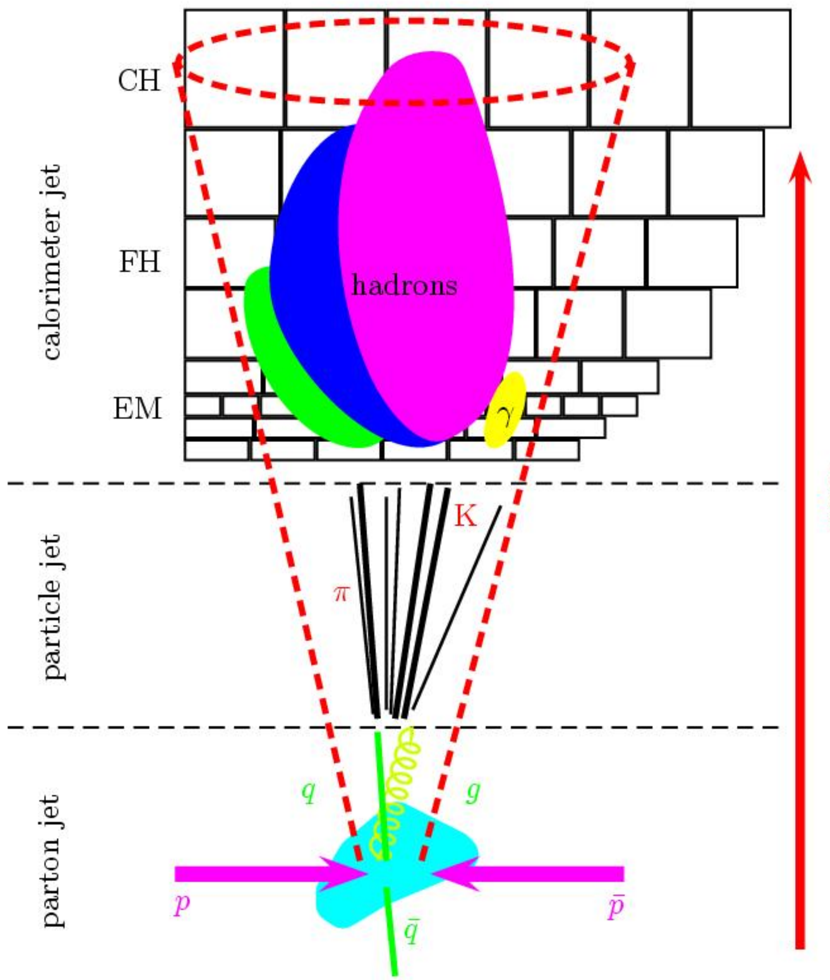
underlying event
and minimum
bias events

Sudakov form factors

jets and jet reconstruction

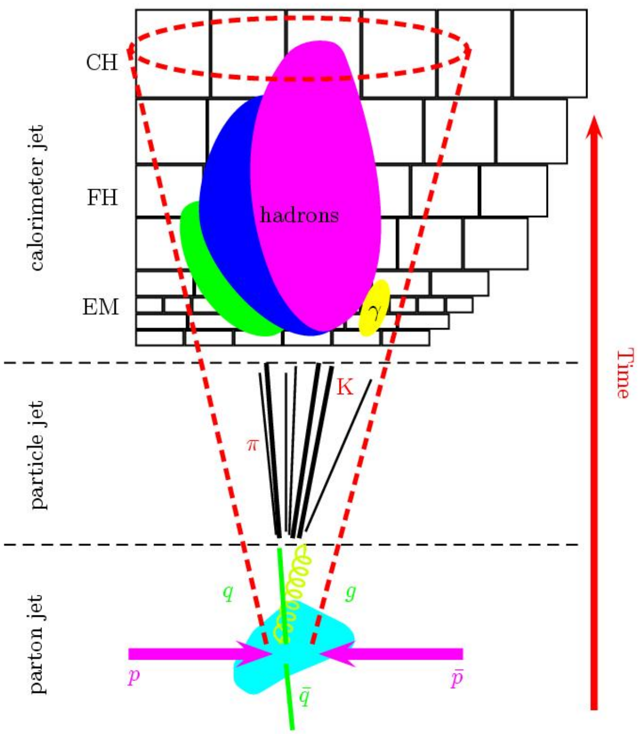
Jets

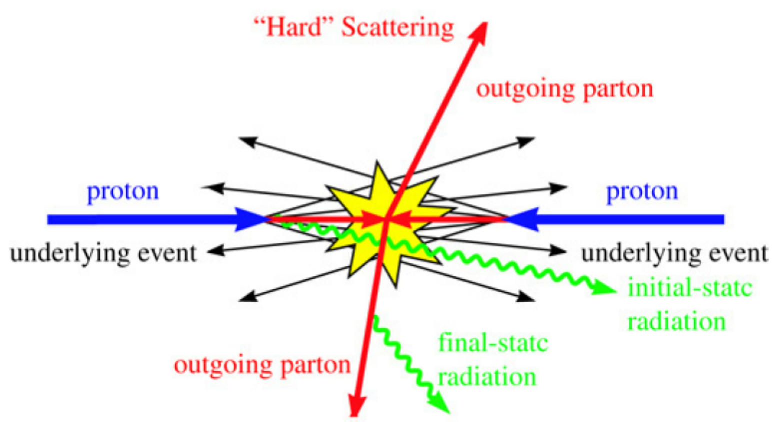
- Most of the interesting physics signatures at the Tevatron, LHC and ILC involve final states with jets of hadrons
- A jet is reconstructed from energy depositions in calorimeter cells and/or from charged particle track momenta, and ideally is corrected for detector response and resolution effects so that the resultant 4-vector corresponds to that of the sum of the original hadrons
- The jets can be further corrected , for hadronization effects, back to the parton(s) from which the jet originated,or the theory can be corrected to the hadron level
- The resultant measurements can be compared back to parton shower predictions, or to the short-distance partons described by fixed-order pertubative calculations



…another word about jets

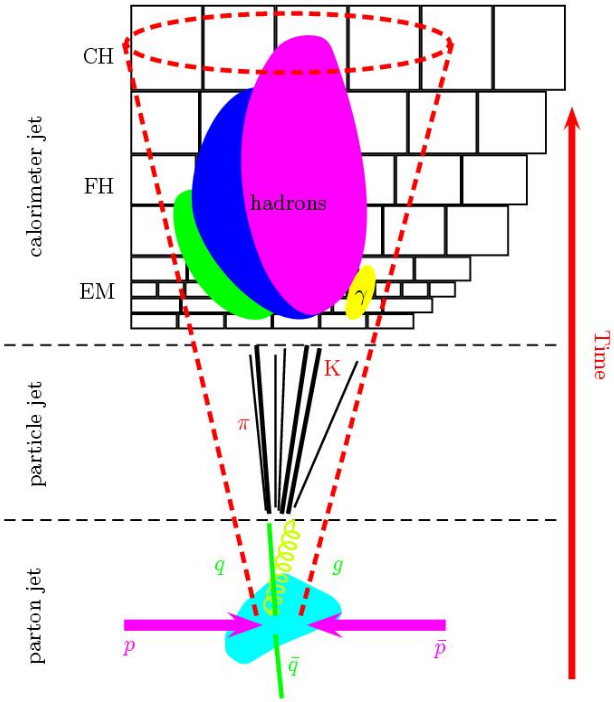
- We pick out from the incident beam particles, the short-distance partons that participate in the hard collision
- The partons selected can emit radiation prior to the short distance scattering leading to initial state radiation
- The remnants of the original hadrons, with one parton removed, will interact with each other, producing an underlying event
- Next comes the short-distance, large momentum transfer scattering process that may change the character of the scattering partons, and/or produce more partons
  - the cross section for this step is calculated to fixed order in pQCD

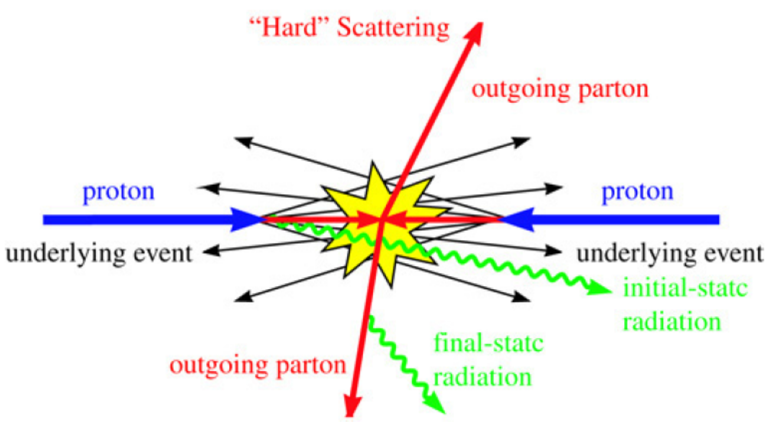




…still another word about jets

- Then comes another color radiation step, when many new gluons and quark pairs are added to the final state
  - this step is dominated by collinear/soft radiation, hence jets
- The final step in the evolution to the long distance states involves a nonperturbative hadronization process that organizes the colored degrees of freedom
- This non-perturbative hadronization step is accomplished in a model-dependent fashion





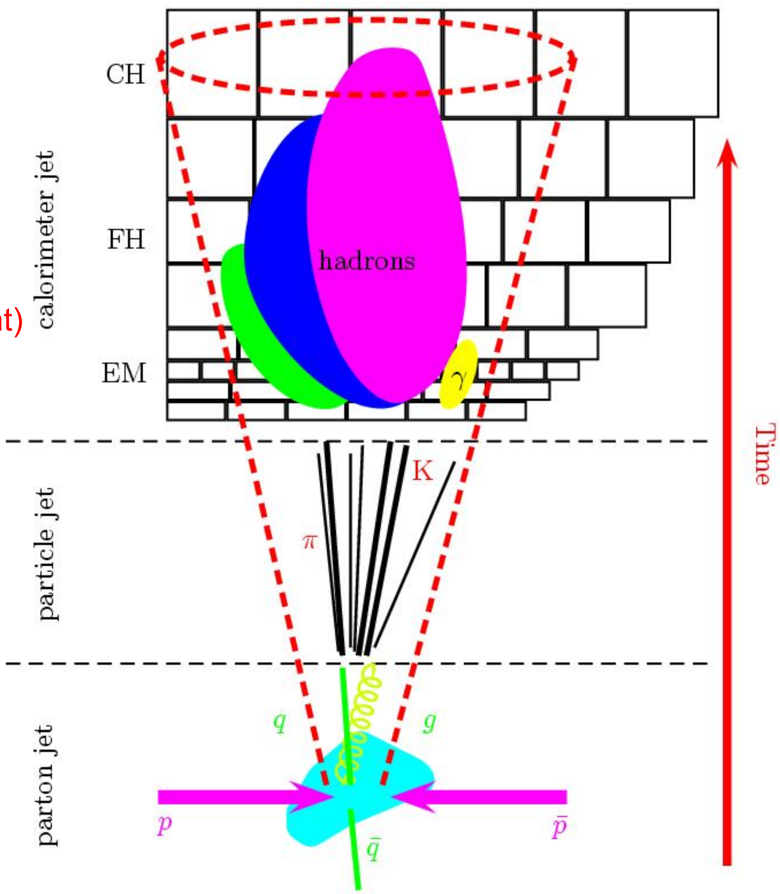
…still another word about jets

- One of the primary goals for jet physics for any experiment is to measure the 4-vector of a jet with the highest precision possible
- Jet measurements can either be calorimeter-based, tracking based, or a combination of the two measurements (particle flow)
- Calorimeter-based measurements are more 'universal' in that the entire energy of the jet is determined, rather than just the track portion
  - and use is made of the full rapidity coverage of the detector, rather than typically just the central region
- Calorimeter-based measurements have been dominant in collider physics to date, but hybrid techniques are/have been developed to obtain the ultimate jet energy resolution

typical energy resolution of $\frac{\sigma}{E} \approx \frac{few - 20\%}{\sqrt{E}}$ for EM showers and $\frac{\sigma}{E} \approx \frac{50 - 100\%}{\sqrt{E}}$ for hadron showers (ignoring constant terms for the moment)

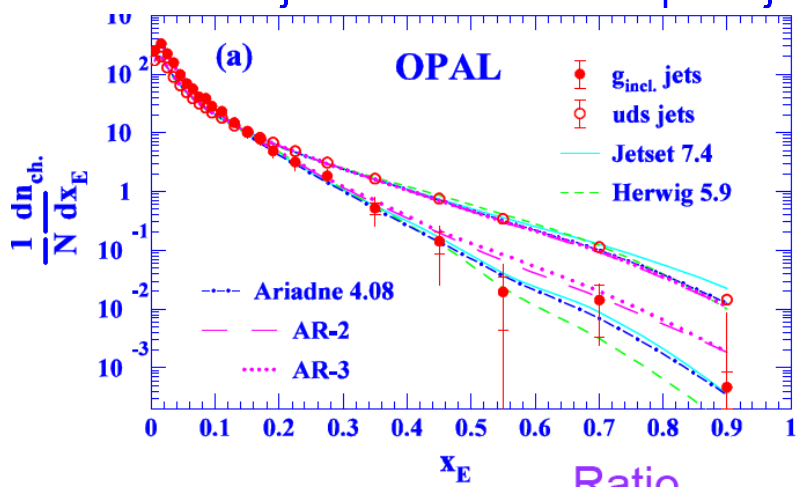
typical momentum resolution of

$$\frac{\sigma_{pT}}{p_T} \approx \left(few X 10^{-4}\right) p_T$$

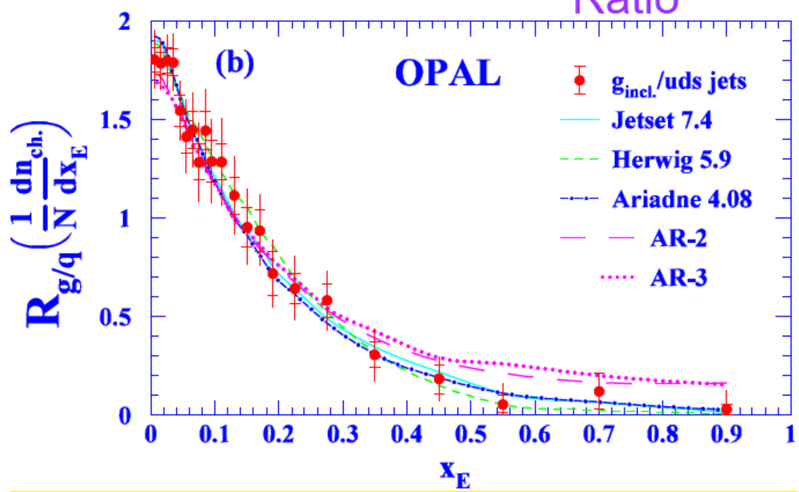


Jet Properties

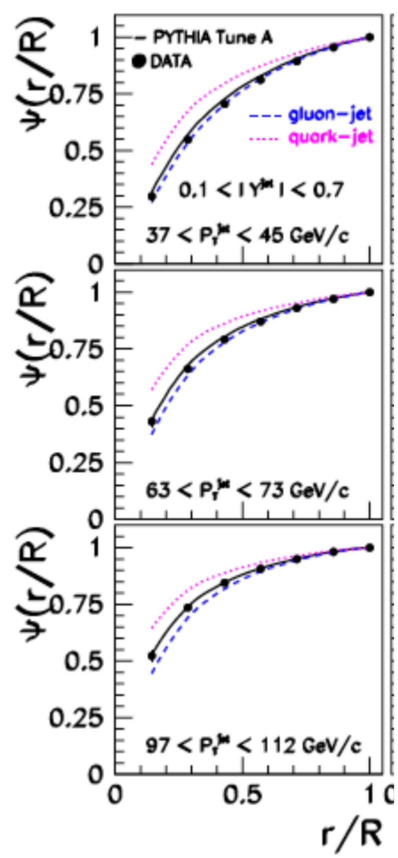
- Most of particles in a jet are at low z, i.e. carry a low fraction of the total jet momentum
- Gluon jets are softer than quark jets

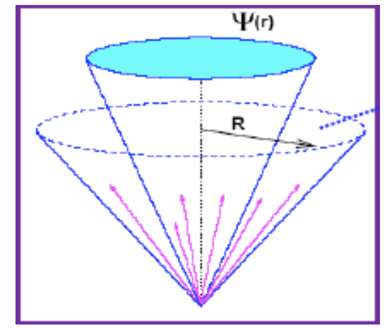


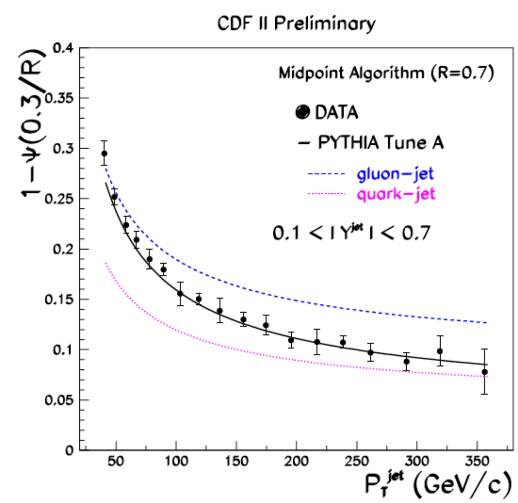
Ratio



Most of energy is in core of jet. Jets get more collimated as the p_T grows. Quark jets are more collimated than gluon jets.





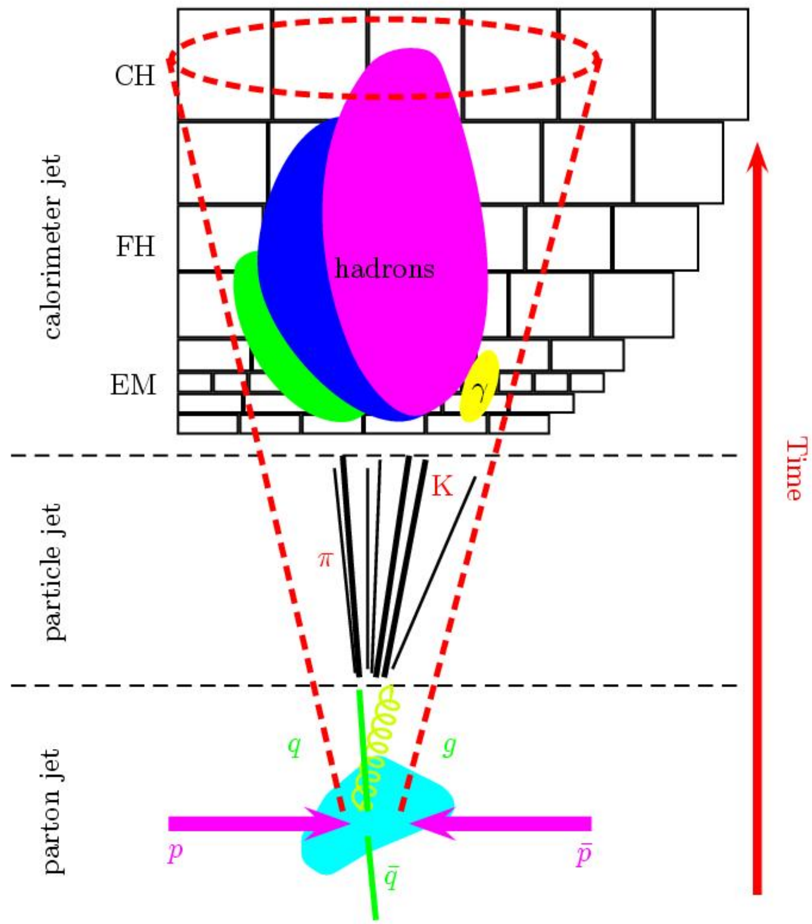


Jets and hadrons

- Jets are composed of multiple hadrons and photons and typically have an angular area (for R=0.7) of ~1.5 steradians
- Thus, for a inner calorimeter radius of 1.2 m, a jet area of ~30,000 cm^2 at η=0
- Smaller at forward rapidities
- Hadrons are 1 fm across
- Pulling out my copy of Iwata (from my SSC days)
- Electromagnetic showers have a transverse area of $\pi R^2_{Moliere} \sim \pi (2cm)^2 = 12.5\ cm^2$
- Hadronic showers have a transverse area of (for 95% containment) $\sim \pi \lambda_{int}^2$, or (using λ= 20 cm), 1250 cm^2, with a much tighter core
- Thus, there's room for a lot of electromagnetic and hadronic showers in a typical jet, without them all overlapping, even at forward rapidities

A complication

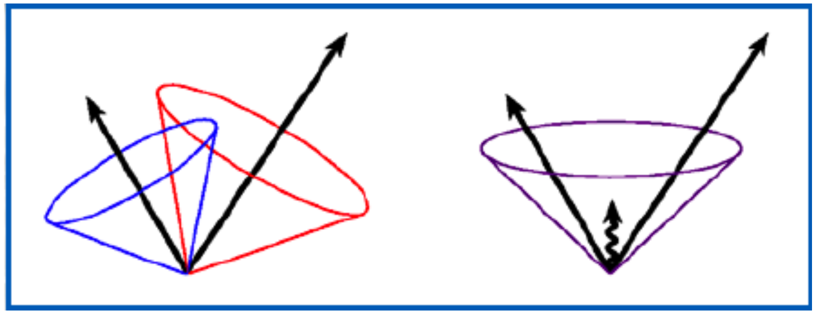
- A parton is not an electron or a photon
    - it’s not an observable per se
    - there’s more physics tied in to/ necessary for jet measurements than for electrons, muons, photons
- A jet algorithm is needed to connect the observed energy/momentum back to the hadron level (and to understand the connection between the hadron and the parton level)
- For the optimal connection, the jet algorithm must give similar results at the parton/hadron/detector levels AND the physics (and background) in the data must be well-simulated in the fixed order or parton shower Monte Carlo programs to which comparisons are made
- Limitations due to jet algorithms may be at the level of 0.5%(my guess)



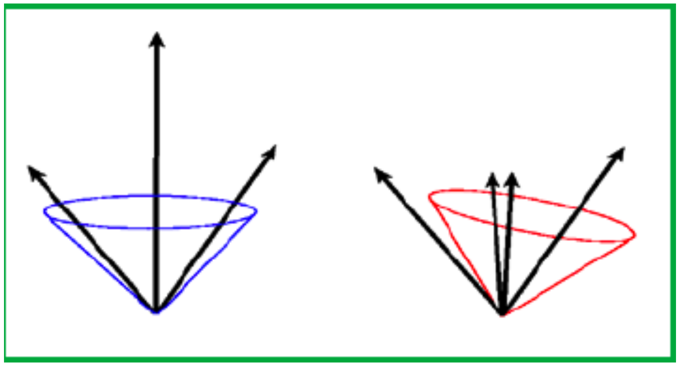
What do I want out of a jet algorithm?

- It should be fully specified, including defining in detail any pre-clustering, merging and splitting issues
- It should be simple to implement in an experimental analysis, and should be independent of the structure of the detector
- It should be boost-invariant
- It should be simple to implement in a theoretical calculation
  - it should be defined at any order in perturbation theory
  - it should yield a finite cross section at any order in perturbation theory
  - it should yield a cross section that is relatively insensitive to hadronization effects
- Algorithms in use at the LHC, antikT, kT, SISCone, satisfy these requirements

- It should be IR safe, i.e. adding a soft gluon should not change the results of the jet clustering

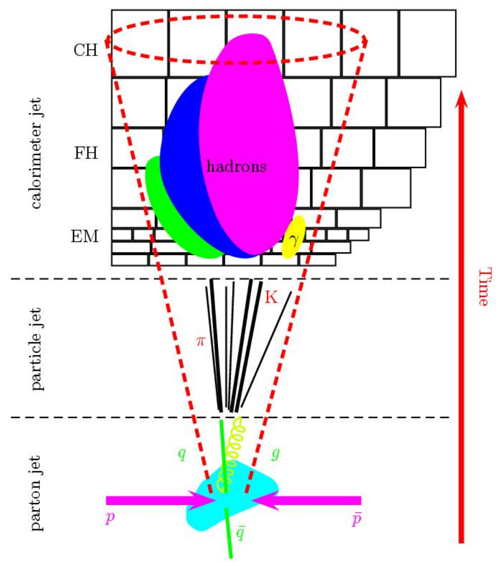


- It should be collinear safe, i.e. splitting one parton into two collinear partons should not change the results of the jet clustering



Choosing jet size

- **Experimentally**
  - in complex final states, such as W + n jets, it is useful to have jet sizes smaller so as to be able to resolve the n jet structure
  - this can also reduce the impact of pileup/ underlying event



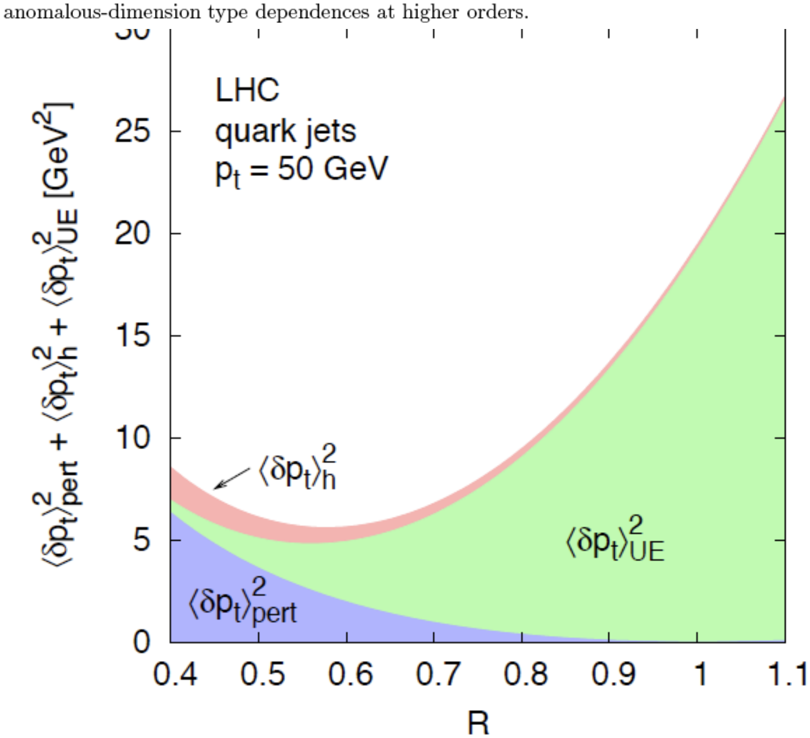
- **Theoretically**
  - hadronization effects become larger as R decreases
  - for small R, there are ln R perturbative terms that can become noticeable
  - this restriction in the gluon phase space can affect the scale dependence, i.e. the scale uncertainty for an n-jet final state can depend on the jet size,

Balancing act for jet precision

- There are fluctuations in radiation, hadronization and in UE subtraction
- Perturbative radiation
  - quark
$$\Delta p_T \approx \frac{\alpha_s C_A}{\pi} p_T \ln R$$
  - gluon
$$\Delta p_T \approx \frac{\alpha_s C_F}{\pi} p_T \ln R$$
- Hadronization
  - quark
$$\Delta p_T \approx \frac{C_F}{R} \bullet 0.4 \text{ GeV}$$
  - gluon
$$\Delta p_T \approx \frac{C_A}{R} \bullet 0.4 \text{ GeV}$$
- Underlying event
$$\Delta p_T \approx \frac{R^2}{2} \bullet 2.5 - 15 \text{ GeV}$$

	Dependence of jet $\langle \delta p_t \rangle$ on			
	'partonic' p_t	colour factor	R	$\sqrt{s}$
perturbative radiation	$\sim \alpha_s(p_t)\, p_t$	C_i	$\ln R + \mathcal{O}(1)$	–
hadronization	–	C_i	$-1/R + \mathcal{O}(R)$	–
underlying event	–	–	$R^2 + \mathcal{O}(R^4)$	s^{ω}

Table 1: Summary of the main physical effects that contribute to the relation between the transverse momentum of a jet and that of a parton, together with their dependence on the properties of the parton, the jet radius R and collider centre of mass energy. Cases labelled "–" do not have any dependence on the corresponding variable in a leading approximation, but may develop anomalous-dimension type dependences at higher orders.



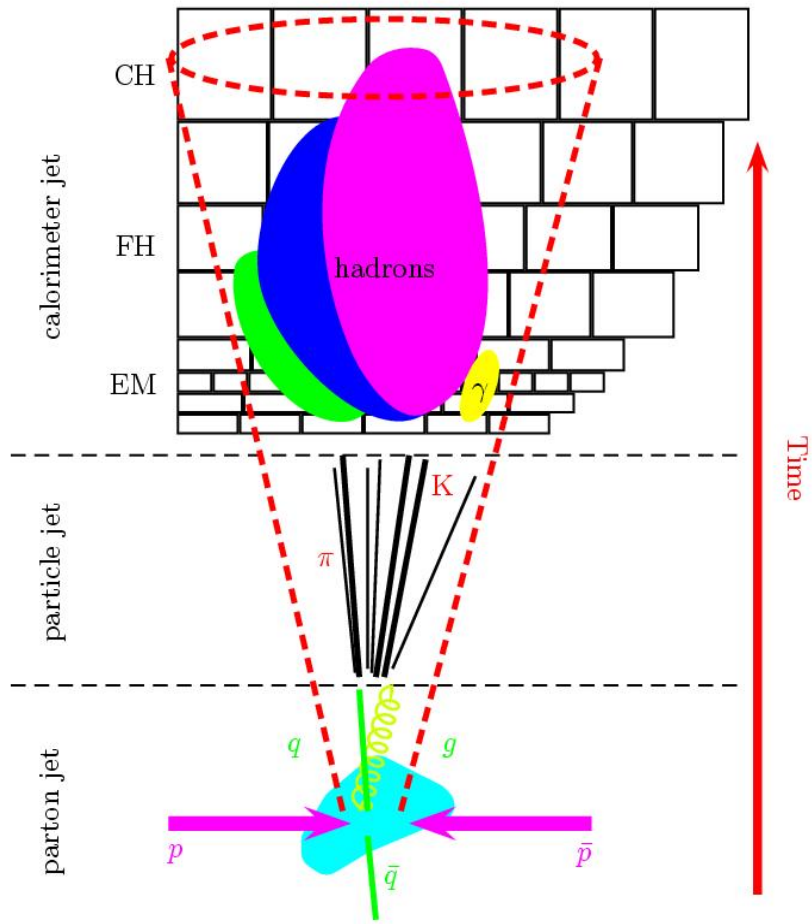
crude analytical estimates
cf. Dasgupta, Magnea & GPS '07

When I was a lad

- …and working on the SSC, everyone was worried about the e/h response and trying to build calorimeters for jet measurements that had equal response to electrons and hadrons
  - looking for magic sampling fractions that would accomplish such
- Now…not so much
  - after experience that e/h≠1 can be calibrated away with sufficient segmentation/information

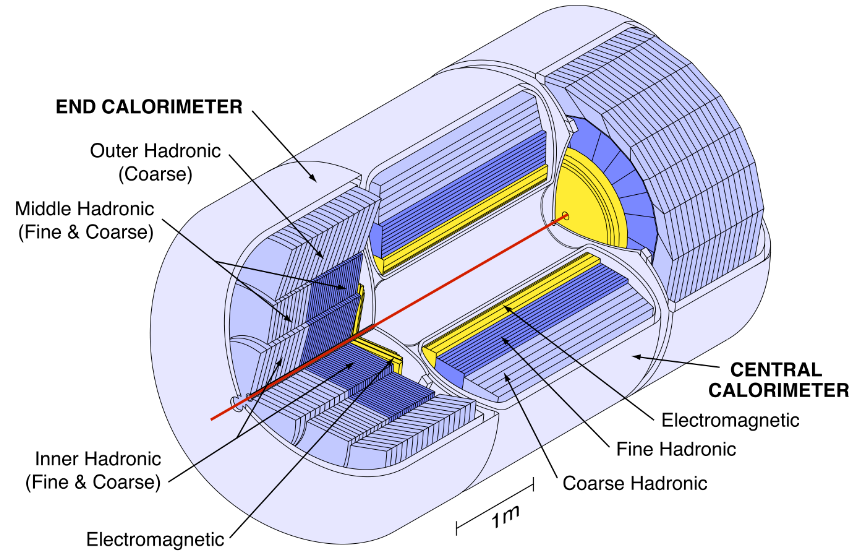
Jet calibration

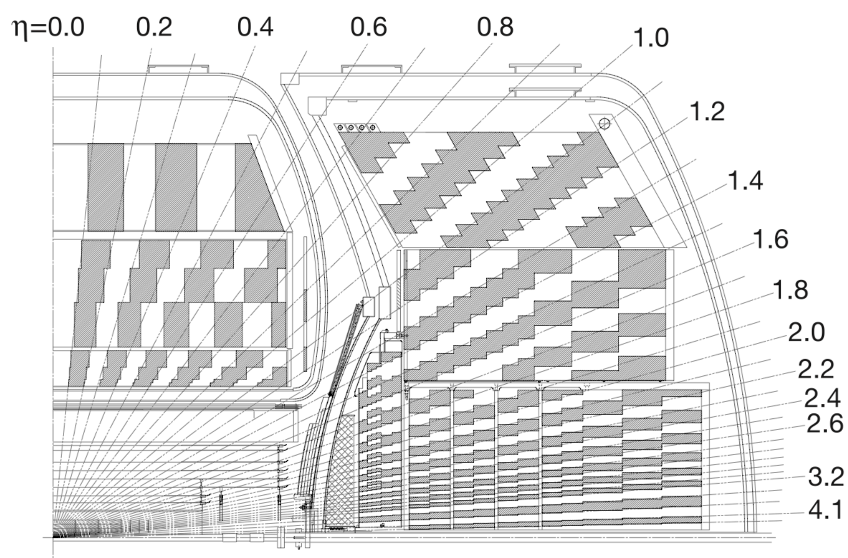
- Different philosophies for jet energy scale calibration
- Global
  - calibrate jet as a complete object
  - use processes such as γ+jet to relate jet scale to EM scale
  - …or use measured detector response to single particles and knowledge of fragmentation function
- Local
  - calibrate 'blobs' of energy in η,ϕ,z (depth) back to hadron level
- Particle flow
  - make use of tracking information when it is more precise than calorimeter information
  - avoid double-counting (that's the trick); the so-called `confusion term'



D0: Run II

- U-LAr calorimeter
  - to get e/h close to 1
  - my post-diction: if D0 were built today, it would use lead as absorber
- Detailed shower information
  - 8 depth segments
  - $\Delta\eta X \Delta\phi \sim 0.1X0.1$
  - finer at EM shower max





Global jet corrections: D0

- Jet energy scale correction involves a number of sub-corrections, derived and applied in a sequential manner
  - O: energy not associated with hard scatter
  - R: lower calorimeter response to pions compared to electrons/ photons, losses in uninstrumented regions
  - F_η: inter-calibrate response as a function of η
  - S: correct for shower leakage outside jet
- Absolute response correction measured by applying MPF method to selected photon + jet events
  - central photon |η|<1.0
  - central jet |η|<0.4
  - correction on order of 30%
- MPF method allows the energy response to be translated to non-central rapidity regions

$$E_{jet}^{ptcl} = \frac{E_{jet}^{raw} - O}{F_\eta \cdot R \cdot S} \cdot k_{bias}$$

E_{jet}^{ptcl}: corrected jet energy

E_{jet}^{raw}: uncorrected jet energy

O: offset energy correction

F_η: relative response correction (η-intercalibration)

R: absolute response correction

S: showering correction

k_{bias}: correction for remaining biases

Missing E_T Projection Fraction Method: γ+jet

Particle Level | Detector Level

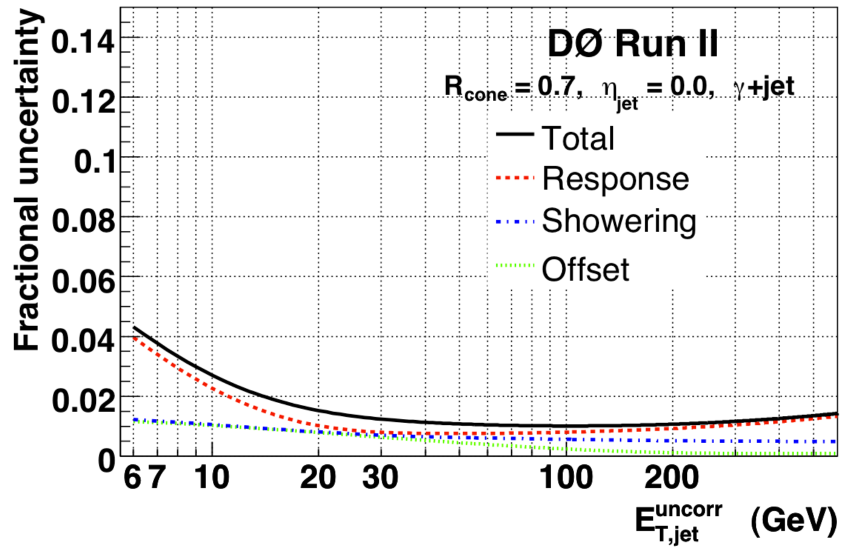
$\vec{p}_{T,\gamma} + \vec{p}_{T,had} = \vec{0}$ $\qquad$ $\vec{p}_{T,\gamma} + R_{had}\vec{p}_{T,had} = -\vec{E}_T$

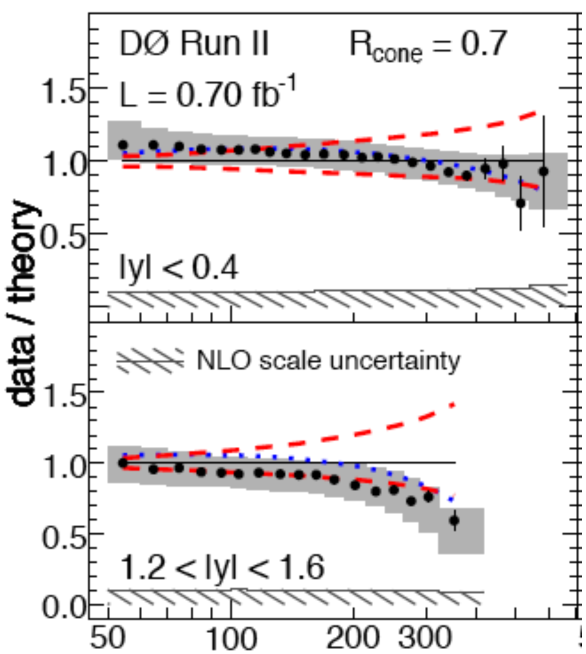
$$R_{had} = 1 + \frac{\vec{E}_T \cdot \vec{p}_{T,\gamma}}{\vec{p}_{T,\gamma}^{\,2}}$$

For back-to-back events : $R_{jet} \approx R_{had}$

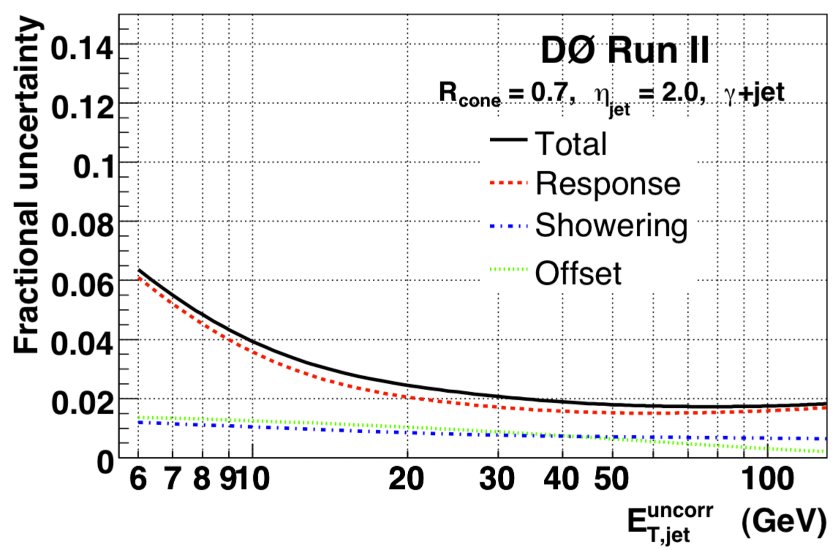
Global corrections: after much work

- Response corrections dominate uncertainty
- JES uncertainty of ~1% in fairly wide p_T range
  - best that I know of to date
- Some degradation when transferring response to forward rapidities





result is small systematic on inclusive jet cross section, for example



ATLAS detector

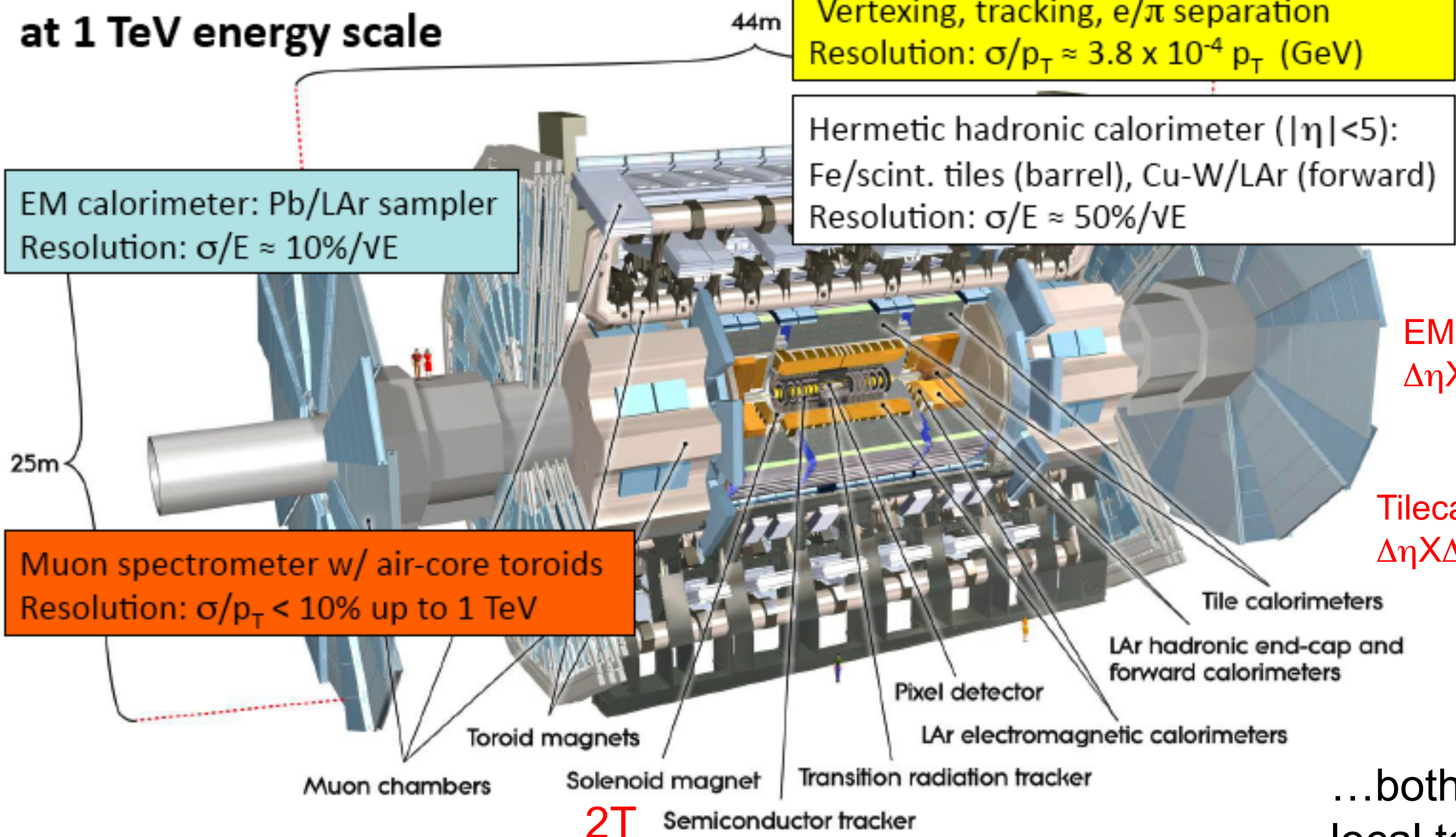
Designed for discovery at 1 TeV energy scale

Inner detector: Si strips/pixels;TRT straws)
Vertexing, tracking, e/π separation
Resolution: $\sigma/p_T \approx 3.8 \times 10^{-4}\, p_T$ (GeV)

Hermetic hadronic calorimeter ($|\eta|<5$):
Fe/scint. tiles (barrel), Cu-W/LAr (forward)
Resolution: $\sigma/E \approx 50\%/\sqrt{E}$

EM calorimeter: Pb/LAr sampler
Resolution: $\sigma/E \approx 10\%/\sqrt{E}$

Muon spectrometer w/ air-core toroids
Resolution: $\sigma/p_T < 10\%$ up to 1 TeV



2T

$e/\pi \sim 1.3$ for calorimeters for ~30 GeV pions

EM: 4 depth segments
$\Delta\eta \mathrm{X} \Delta\phi \sim 0.025\mathrm{X}0.025$

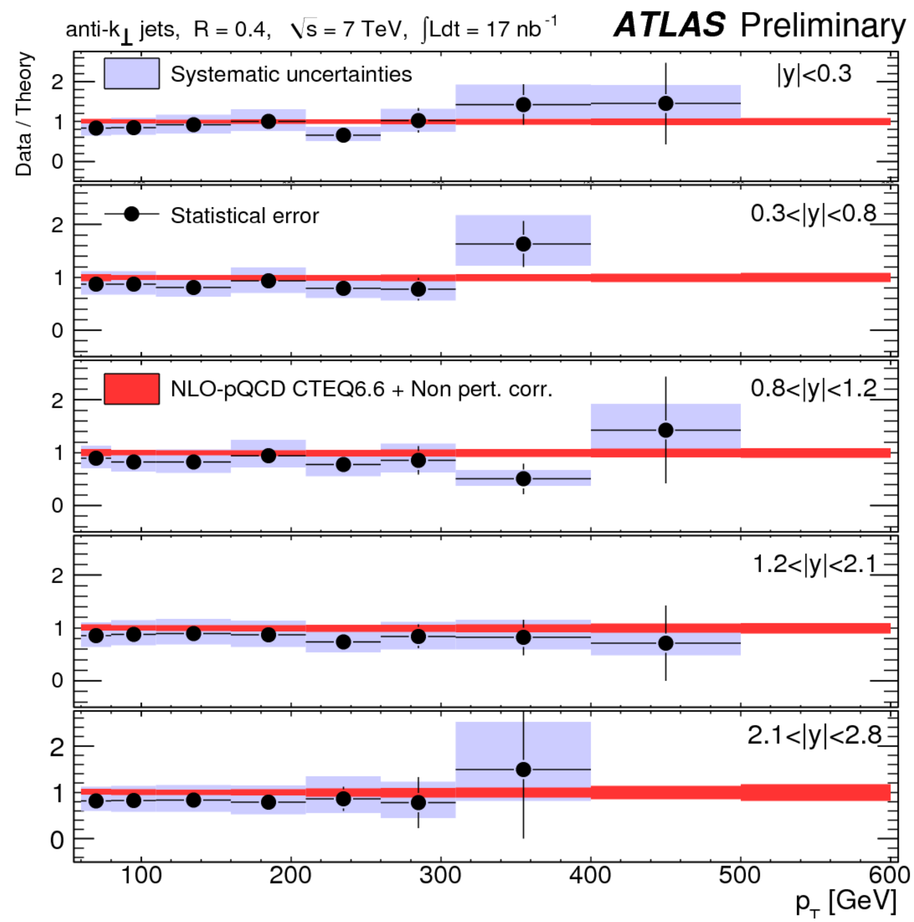
Tilecal: 3 depth segments
$\Delta\eta \mathrm{X} \Delta\phi \sim 0.1\mathrm{X}0.1$

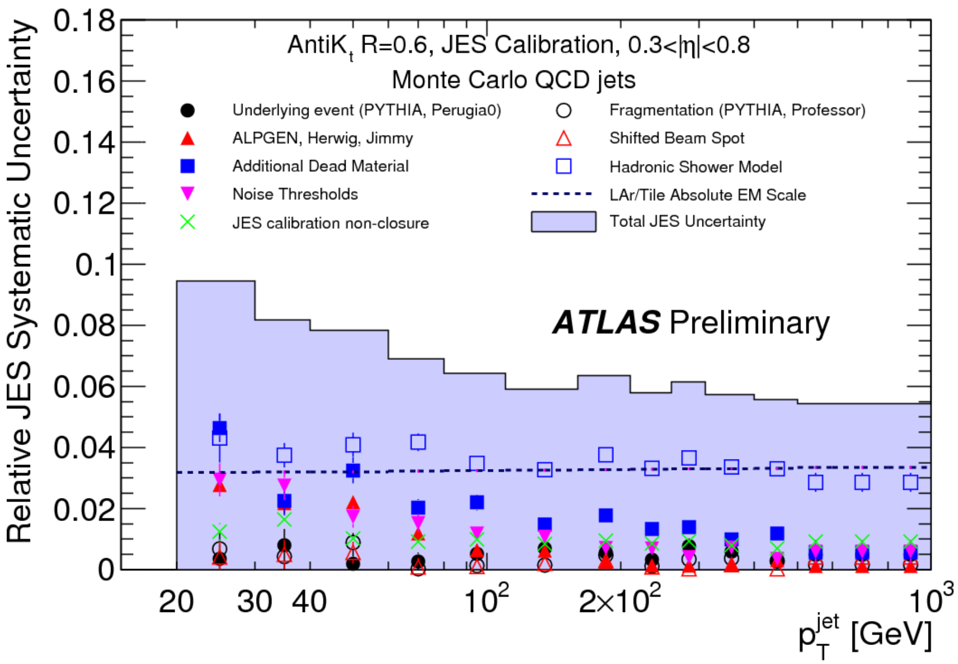
…both global and local techniques for jet calibration

ATLAS JES: inclusive jet production

- First results using global calibration
- Very conservative estimate for size of JES uncertainty
- Is being reduced as more data is accumulated/analyzed

…even with 17 nb-1 (in this publication), exceed Tevatron range

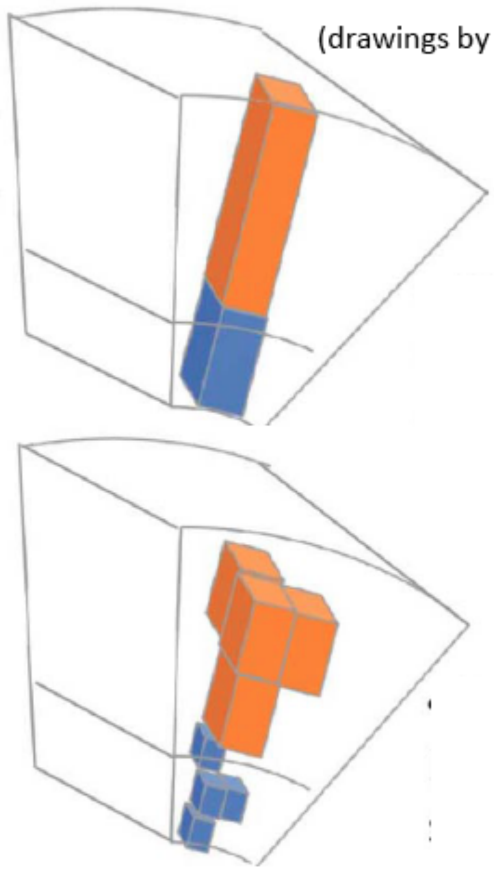




ATLAS: local calibration

- Form topological cluster of connected energies
- Correct energy back to (close to) hadron level

(drawings by K. Perez, Columbia University)

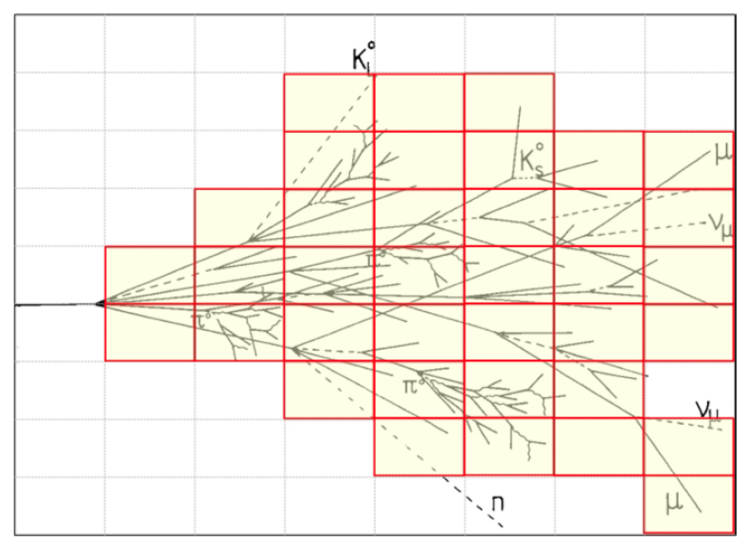


Unbiased calorimeter tower is a "slab" of energy in a regular pseudorapidity-azimuth grid (each tower covers the same area in these coordinates)

Topological cell cluster is a "blob" of energy dynamically located inside the calorimeter (even crossing sub-detector boundaries)

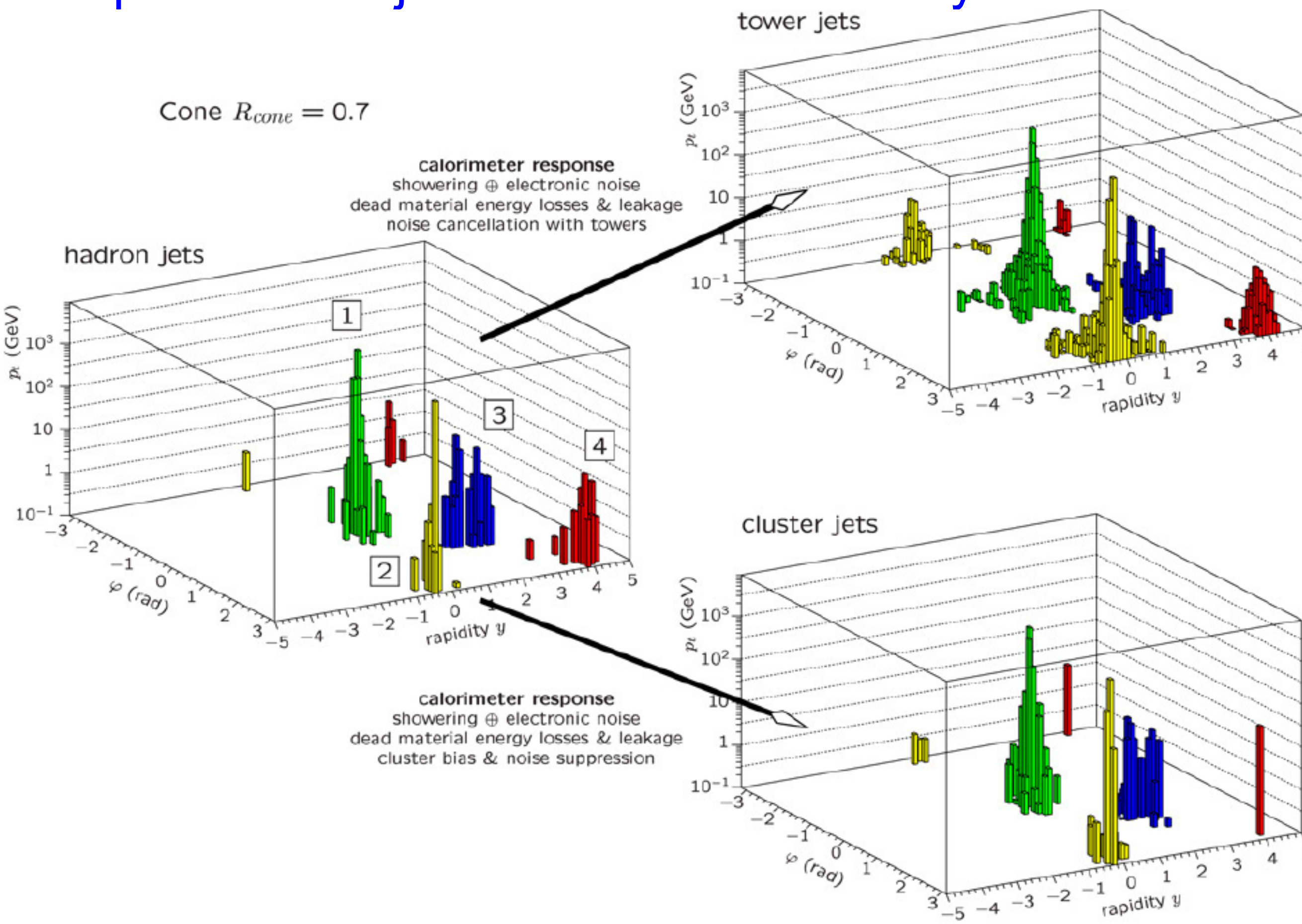
Use local energy density to determine calibration for topocluster->locally calibrated topocluster

high densities: electromagnetic showers
low densities: hadronic showers



ATLAS jet reconstruction

- Using calibrated topoclusters, ATLAS has a chance to use jets in a dynamic manner not possible in any previous hadron-hadron calorimeter, i.e. to examine the impact of multiple jet algorithms/ parameters/jet substructure on every data set



blobs of energy in the calorimeter correspond to 1/few particles (photons, electrons, hadrons); can be corrected back to hadron level

rather than jet itself being corrected

similar to running at hadron level in Monte Carlos from jet review paper

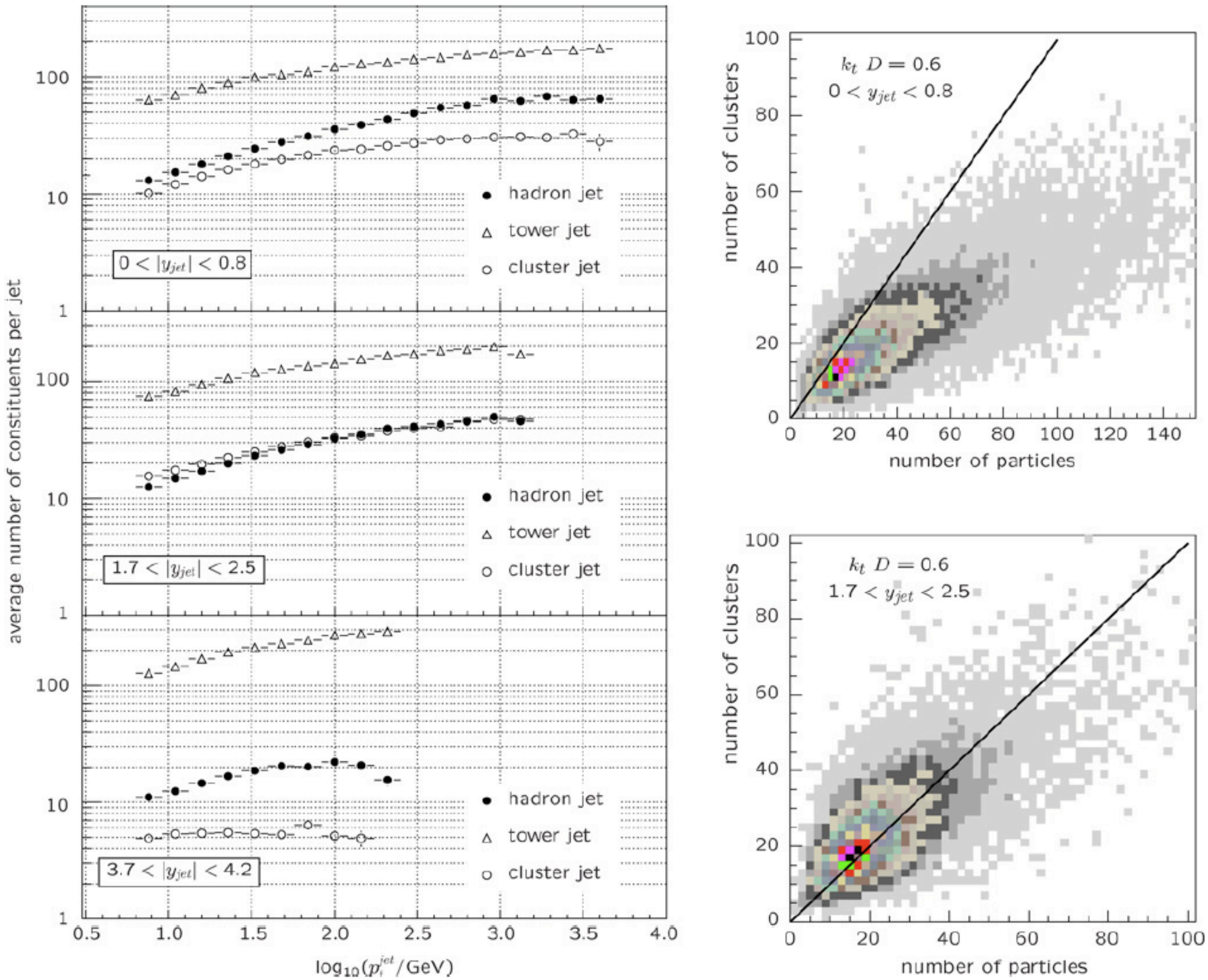
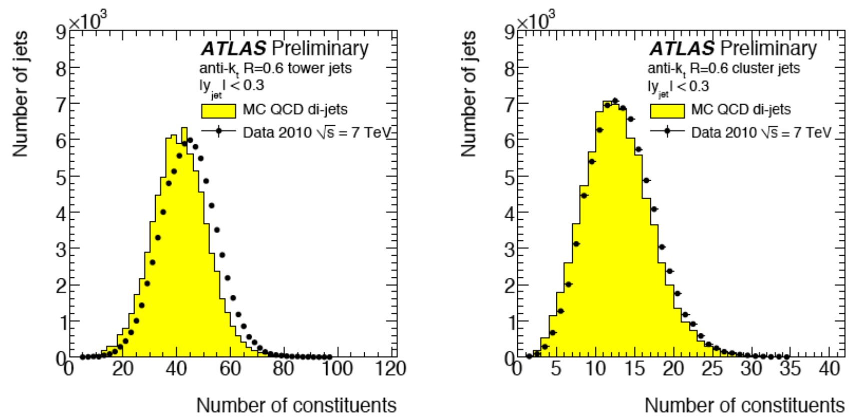


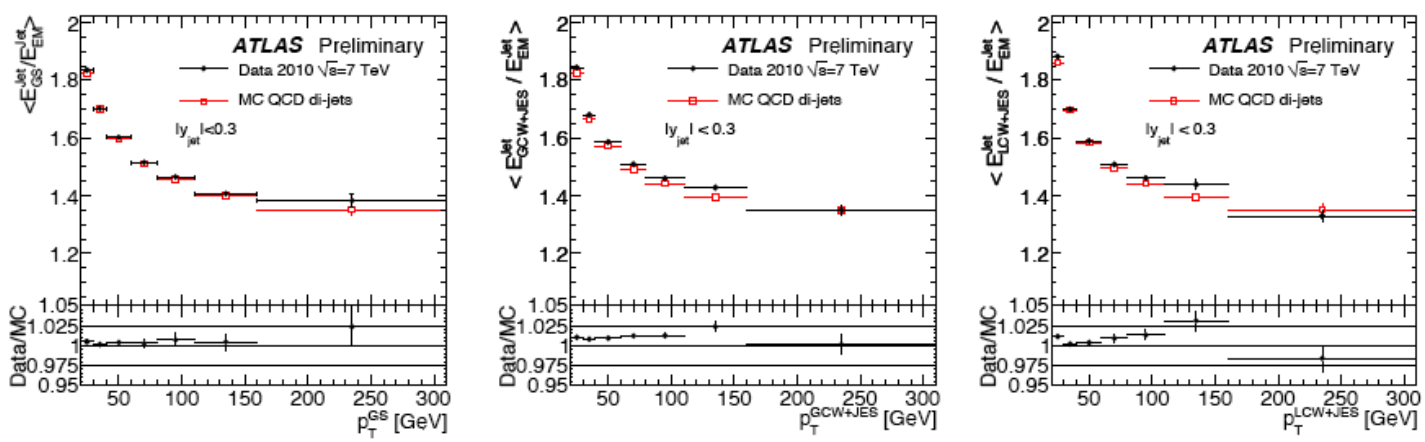
Fig. 47. The number of constituents for hadron, cluster, and tower k_T jets ($D = 0.6$) as a function of the jet p_T for simulated central events in ATLAS, in various regions of rapidity y (left). The right figure shows the number of clusters versus the number of particles in matched cluster and hadron jets in the central and endcap region, from the same simulated data.

Thus far…

- Good agreement between collision data and Monte Carlo for # topoclusters/jet, calibration of topocluster jets
- More to be made public soon
- Current JES precision: ~3-4%; ultimate precision of topocluster jets should be 1% or less (after 100 pb^{-1})



(a) Number of towers per jet (b) Number of clusters per jet

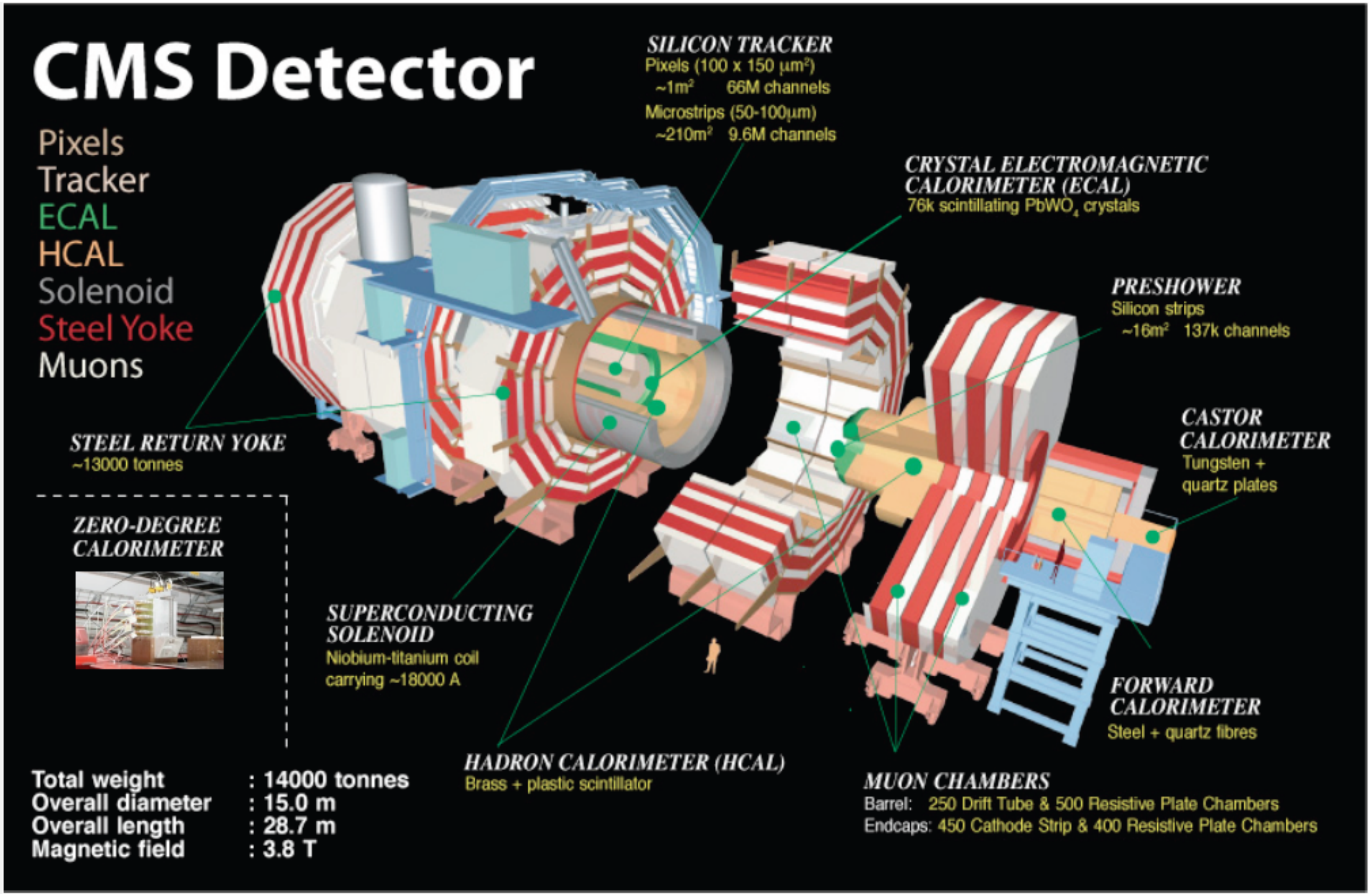


(a) Global sequential calibration (b) Global cell-weighting calibration (c) Local cluster calibration

Figure 25: Mean calibrated jet energy over uncalibrated jet energy as a function of calibrated jet p_T for jets constructed of topological clusters calibrated with (a) the global sequential, (b) the global cell energy-density weighting, and (c) local cluster weighting calibration schemes. The mean value is shown as obtained in data (black points) and in Monte Carlo simulation (red open squares).

CMS

$\sigma/p_T \sim 1\text{X}10^{-4}\, p_T$ (1% at 100 GeV)

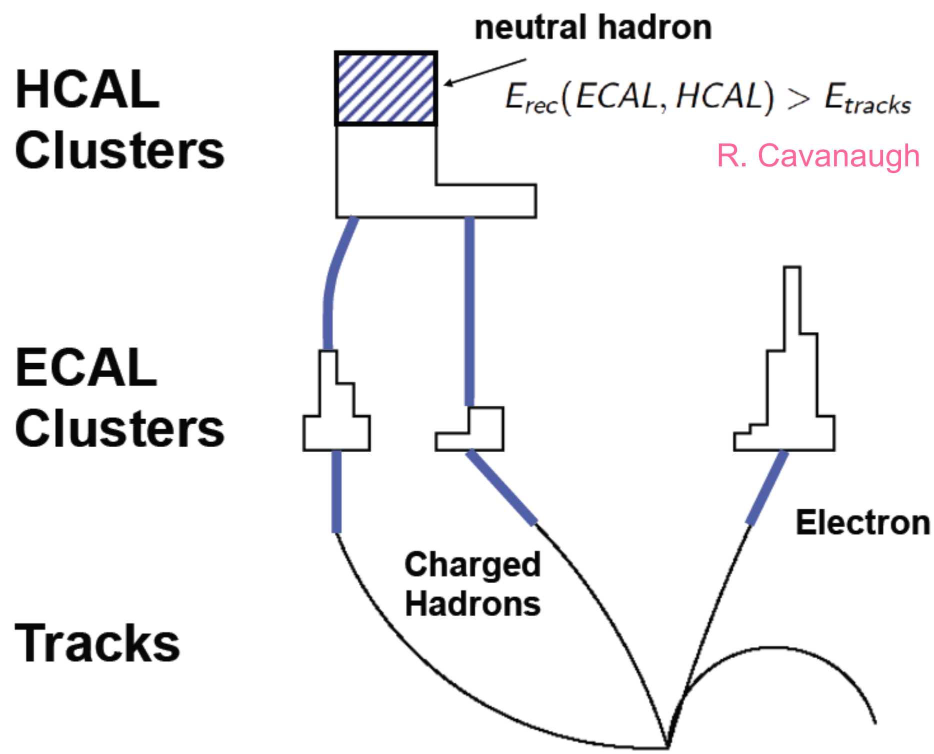


very different EM/HAD calorimeters

Particle flow: CMS

- Find and remove muons (σ_{track})
- Find and remove electrons (min [σ_{track},σ_{ECAL}])
- Find and remove converted photons (min[σ_{track},σ_{ECAL}])
- Find and remove charged hadrons (σ_{track})
- Find and remove V0's (σ_{track})
- Find and remove photons (σ_{ECAL})
- Left with neutral hadrons (σ_{HCAL} + fake)

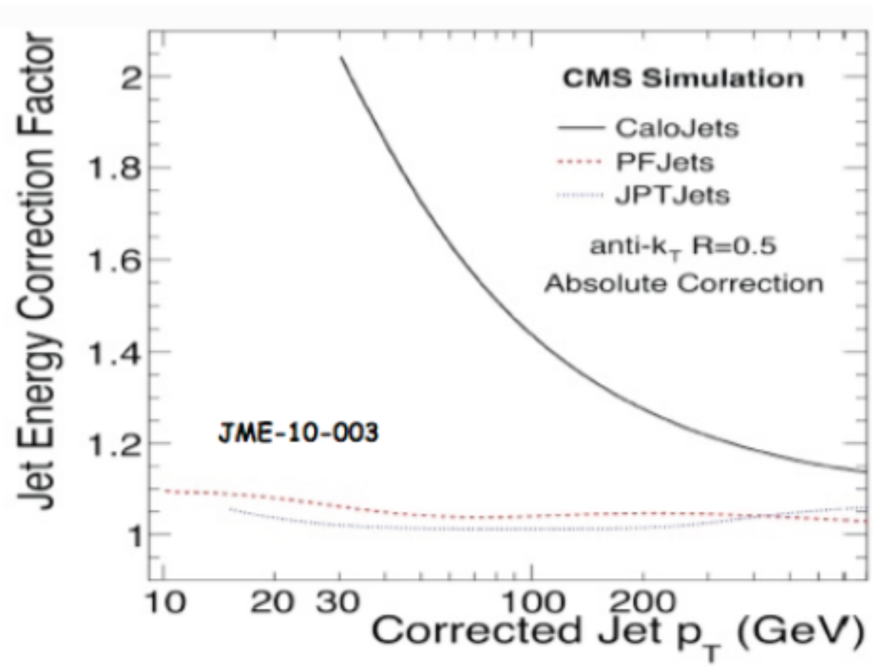
- Use above list to describe entire event



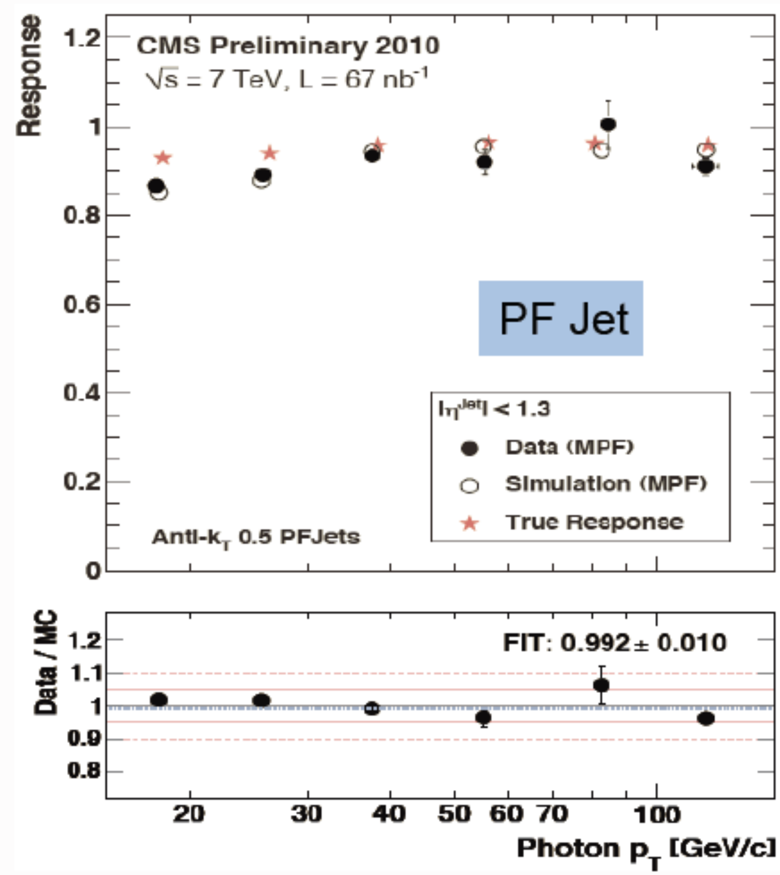
•charged hadrons: typically 65% of energy (1% for 100 GeV tracks)
•photons: typically 25% of energy (2%/sqrt(E))
•neutral hadrons: typically 10% of energy 100%/sqrt(E)

Particle Flow

- Jet corrections much smaller for PF (particle flow) than for CaloJets

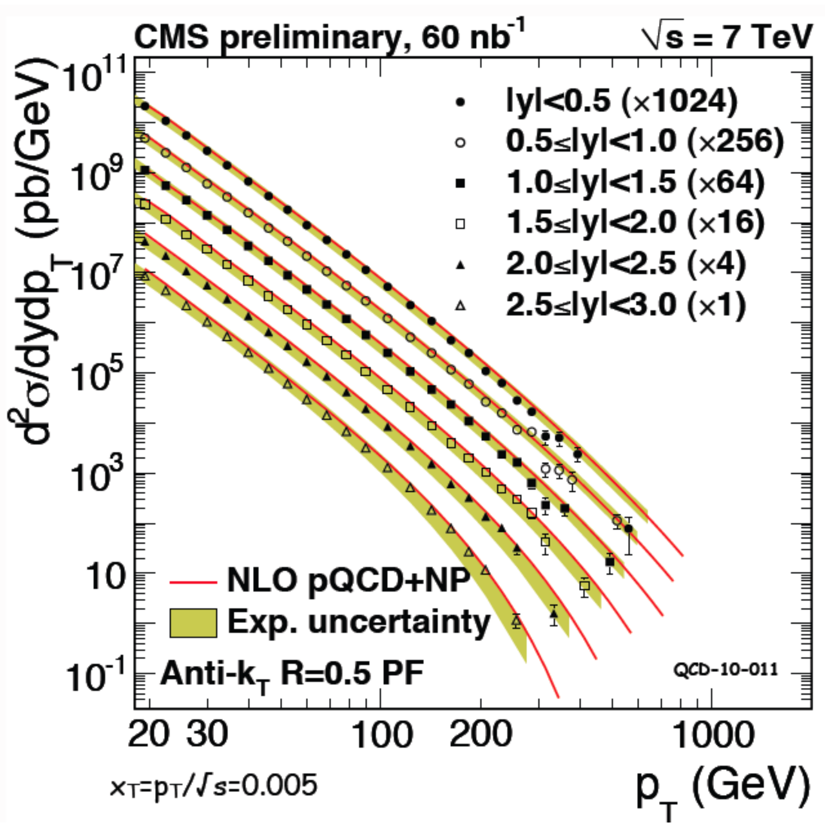


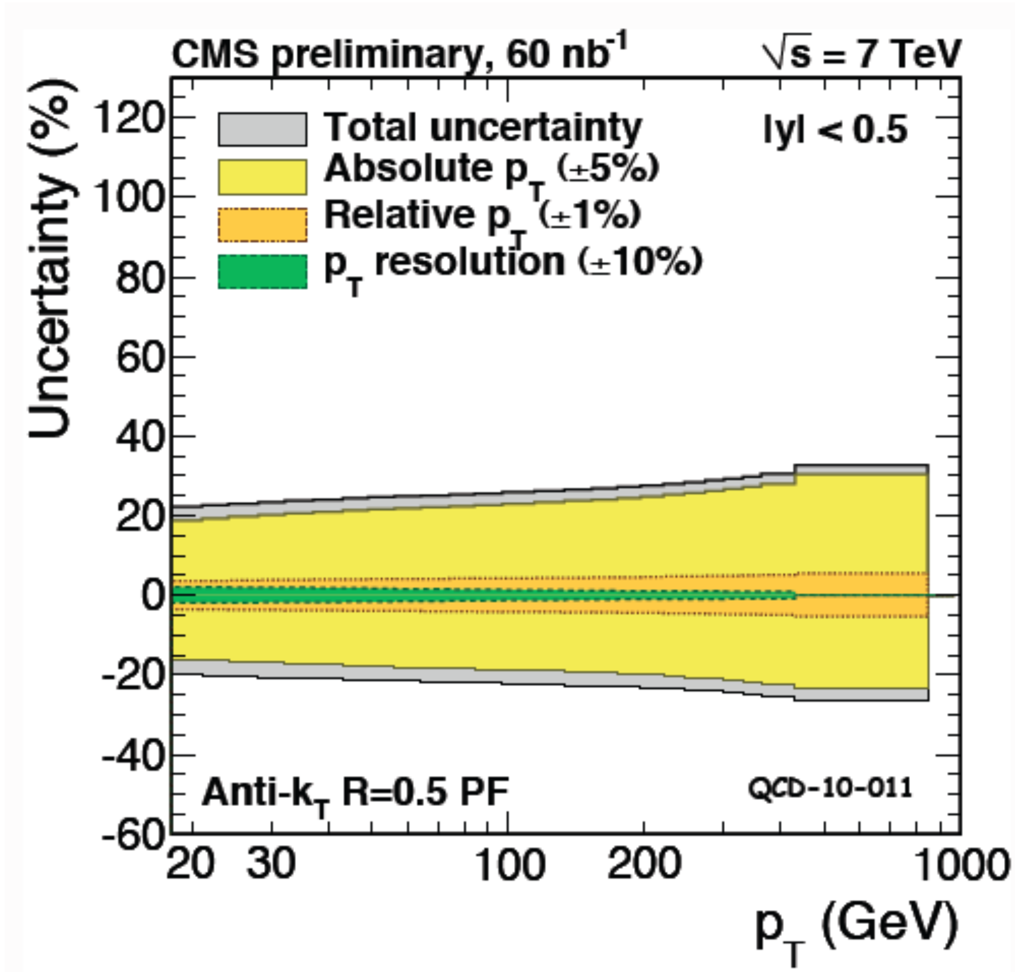
Missing-E_T projection fraction method (**MPF**, from D0) uses MET to measure the balance and is less sensitive to QCD radiation



CMS particle flow

- Preliminary results using particle flow
- 5% JES uncertainty
- Expected to go to 1% with more data/experience





Jet finding at the LHC

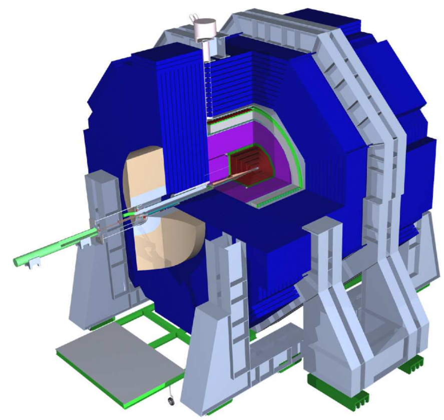
- Jets are dynamic objects
- Different resolution scales and different algorithms can uncover different aspects of jet properties and the underlying physics, whether it be derived from QCD alone or QCD+BSM
- Just as important as precision on the determination of jet 4-vectors is flexibility in jet reconstruction, so that the events can be analyzed in just as dynamic a fashion as they were created
- Luckily:
  - with locally calibrated topoclusters (ATLAS), particle flow (CMS), the detector tools are available to make this possible
  - using software tools such as FastJet, SpartyJet

ILC and CLIC

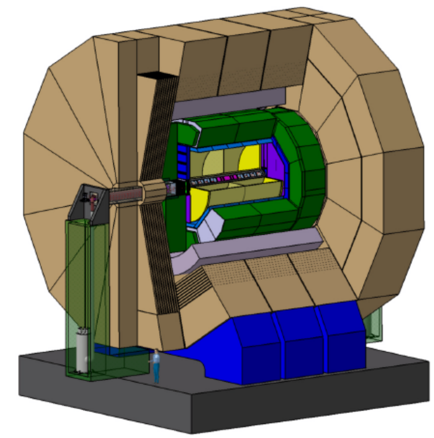
- Can define specific criterion
  - should be able to distinguish between Z->qQ and W->qQ'
- This imposes requirement that dijet mass resolution should be comparable to natural widths of W/Z

$$\frac{\sigma_m}{m} < 2.7\% \approx \frac{\Gamma_Z}{m_Z} \approx \frac{\Gamma_W}{m_W}$$

$$\Rightarrow \frac{\sigma_E}{E} < 3.8\%$$



SiD detector concept



ILD detector concept

- Thus, the need for particle flow techniques
- This is the only one of the detector(s) that I'm going to talk about that has not yet been built
  - and thus is still the subject of much R&D

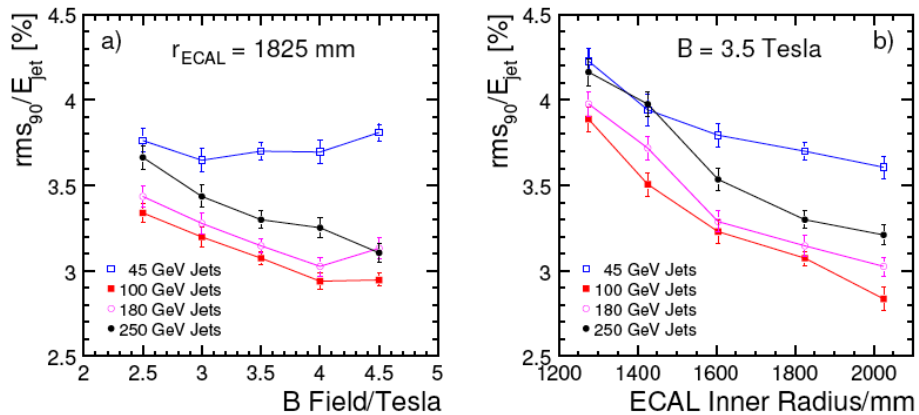
Particle Flow Algorithms (PFAs) have been developed, such as PandoraPDA for ILD and IowaPFA for SiD

I'll give a few examples from PandoraPFA (since it's the first one that I read)

Particle flow

- Particle flow places strong constraints on design of detectors
  - high granularity for both electromagnetic and hadronic calorimeters
  - both calorimeters inside solenoid coil
  - high magnetic field to deflect charged particles away from the core of a jet
  - have to optimize/justify inner radius R of calorimeter, B, thickness of hadronic calorimeter

similar results obtained for SiD



arXiv:1006.3396
ILD letter of intent

FIGURE 2.2-2. a) the dependence of the jet energy resolution (rms_{90}) on the magnetic field for a fixed ECAL inner radius (B=3.5 T corresponds to the LDCPrime model). b) the dependence of the jet energy resolution (rms_{90}) on the ECAL inner radius a fixed value of the magnetic field (R=1825 mm corresponds to the LDCPrime model).

estimated contribution to jet energy resolution from intrinsic calorimeter resolution

imperfect track reconstruction

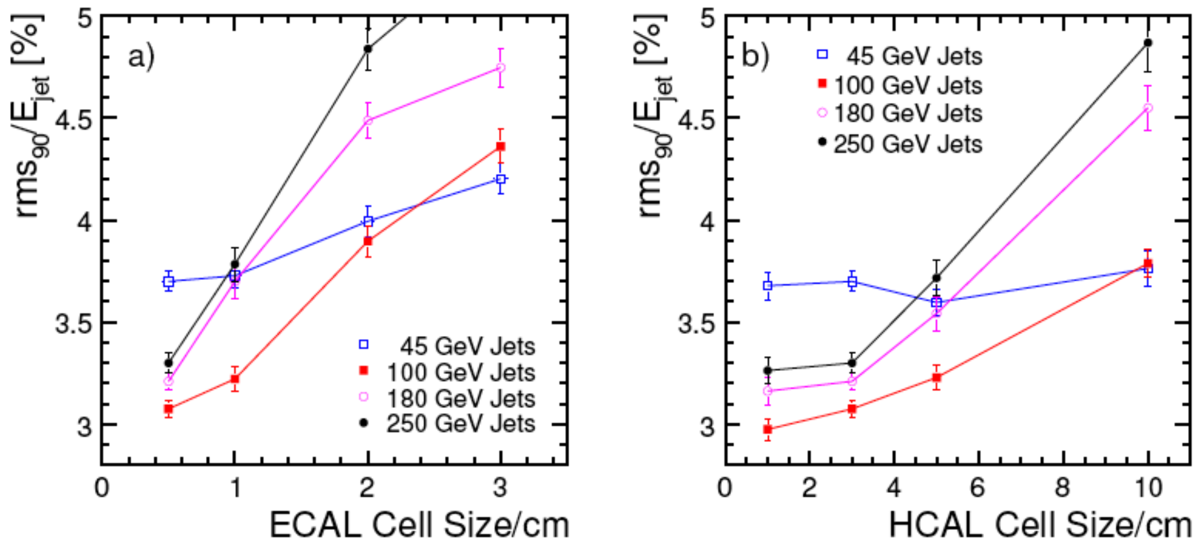
leakage

contribution from the confusion term obtained from fit to data above

$$\frac{\sigma_E}{E} = \frac{21}{\sqrt{E/\mathrm{GeV}}} \oplus 0.7 \oplus 0.004E \oplus 2.1 \left(\frac{R}{1825\,\mathrm{mm}}\right)^{-1.0} \left(\frac{B}{3.5\,\mathrm{T}}\right)^{-0.3} \left(\frac{E}{100\,\mathrm{GeV}}\right)^{0.3} \%$$

R more important than B

Transverse segmentation



arXiv:1006.3396
ILD letter of intent

FIGURE 2.2-4. a) the dependence of the jet energy resolution (rms_{90}) on the ECAL transverse segmentation (Silicon pixel size) in the LDCPrime model. b) the dependence of the jet energy resolution (rms_{90}) on the HCAL transverse segmentation (scintillator tile size) in the LDCPrime model.

- Electromagnetic calorimeter transverse segmentation has to be at least as fine as 10X10mm^2, with preference for 5X5mm^2
  - Si-W or scintillator-W (W for small Moliere radius)
- Hadronic calorimeter transverse segmentation can be achieved with segmentation of 5X5cm^2, with preference for 3X3cm^2
  - steel-scintillator (analog) or steel-RPC (semi-digital)

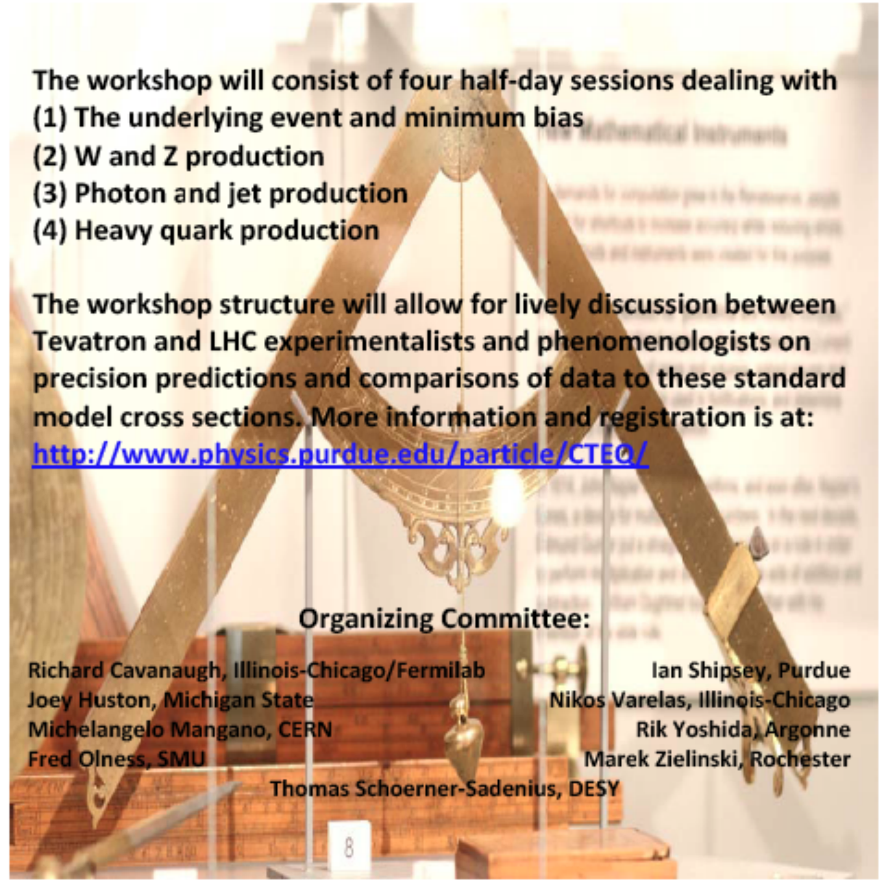
Summary

- We are achieving a precision in jet measurements much better than dreamed of in SSC days
- This has come about not by tuning e/h=1, but by the use of fine calorimeter segmentation and smart thinking, making use of full detector information
- This increased precision, and increased flexibility in jet analyses, will lead to a better understanding of the physics at both hadron-hadron and lepton-lepton colliders
- Further design/cost optimization needed for jet measurements at the ILC

if there is ever a prize for most logos on a Fermilab workshop, we win

Standard Model Benchmarks at the Tevatron and LHC

Fermilab, November 19 & 20, 2010



The workshop will consist of four half-day sessions dealing with
(1) The underlying event and minimum bias
(2) W and Z production
(3) Photon and jet production
(4) Heavy quark production

The workshop structure will allow for lively discussion between Tevatron and LHC experimentalists and phenomenologists on precision predictions and comparisons of data to these standard model cross sections. More information and registration is at: http://www.physics.purdue.edu/particle/CTEQ/

Organizing Committee:

Richard Cavanaugh, Illinois-Chicago/Fermilab
Joey Huston, Michigan State
Michelangelo Mangano, CERN
Fred Olness, SMU
Ian Shipsey, Purdue
Nikos Varelas, Illinois-Chicago
Rik Yoshida, Argonne
Marek Zielinski, Rochester
Thomas Schoerner-Sadenius, DESY

Hosted by: The CTEQ Collaboration, the LHC Physics Centers @ CERN, DESY, FERMILAB and the ATLAS Physics Analysis Center @ ANL

U.S. DEPARTMENT OF ENERGY Fermilab Fermi Research Alliance LLC

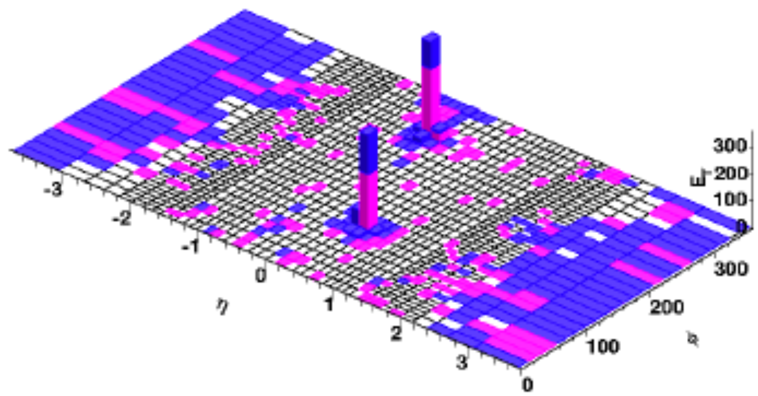
CTEQ LPCC ANL ASC

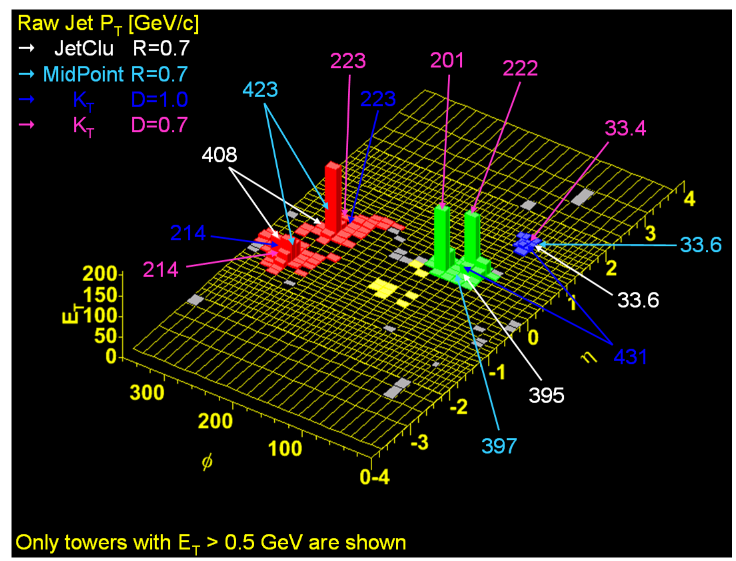
Extras

Back to jet algorithms

- For some events, the jet structure is very clear and there's little ambiguity about the assignment of towers to the jet
- But for other events, there is ambiguity and the jet algorithm must make decisions that impact precision measurements
- If comparison is to hadron-level Monte Carlo, then hope is that the Monte Carlo will reproduce all of the physics present in the data and influence of jet algorithms can be understood
    - more difficulty when comparing to parton level calculations

CDF Run II events





SpartyJet

Sparty

J. Huston, K. Geerlings,
Brian Martin
Michigan State University

P-A. Delsart, Grenoble

http://www.pa.msu.edu/~huston/SpartyJet/SpartyJet.html/

If interested for ATLAS, please contact
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